(Preprint)

MOON AGE AND REGOLITH EXPLORER (MARE) MISSION DESIGN AND PERFORMANCE

Gerald L. Condon* and David E. Lee†

The moon's surface last saw a controlled landing from a U.S. spacecraft on December 11, 1972 with Apollo 17. Since that time, there has been an absence of methodical in-situ investigation of the lunar surface. In addition to the scientific value of measuring the age and composition of a relatively young portion of the lunar surface near Aristarchus Plateau, the Moon Age and Regolith Explorer (MARE) proposal provides the first U.S. soft lunar landing since the Apollo Program and the first ever robotic soft lunar landing employing an autonomous hazard detection and avoidance system, a system that promises to enhance crew safety and survivability during a manned lunar (or other) landing. This report focuses on the mission design and performance associated with the MARE robotic lunar landing subject to mission and trajectory constraints.

INTRODUCTION

This report examines the mission design and associated performance requirement for a robotic spacecraft delivered to a post-trans-lunar injection (TLI) target and bound for a precision lunar landing at a selected location to support surface in-situ sample analysis. The trajectory design for the Moon Age and Regolith Experiment (MARE) includes a combination of a flight profile similar to that of Apollo, and for similar reasons, combined with a unique powered descent flight profile, designed to provide the spacecraft with a high accuracy landing employing a relative navigation sensor suite, that also provides hazard detection and avoidance capability. Launch readiness is targeted for 2021. The mission design produces monthly mission opportunities with multiple daily launch opportunities for each monthly opportunity.

MARE begins with a due east launch of an Atlas 411 (see Figure 1) which delivers the MARE spacecraft to a temporary low Earth orbit (LEO). The launch is timed such that

---

* Senior Engineer, Aeroscience and Flight Mechanics Division, NASA-Johnson Space Center, 2101 Nasa Pkwy, Houston, TX 77058.
† Senior Engineer, Aeroscience and Flight Mechanics Division, NASA-Johnson Space Center, 2101 Nasa Pkwy, Houston, TX 77058.

the LEO parking orbit will be nearly coplanar with the lunar transfer orbit. The upper stage/MARE spacecraft stack then coasts to the preferred phase location for the trans-lunar injection (TLI) burn, which achieves a transfer target to a lunar intercept anywhere from 3 to 8 days after Earth departure, depending upon which of several daily launch opportunities, in a particular month, is accessed. After TLI, the MARE spacecraft and the booster upper stage separate. After achieving a safe separation distance, the upper stage performs a retargeting maneuver for a safe disposal. The MARE spacecraft, now on its trans-lunar coast toward lunar orbit insertion (LOI), performs all maneuvers from this point forward. Along the way, the outbound trajectory design accommodates up to four trajectory correction maneuvers (TCM). TCMs are only performed if the spacecraft trajectory is significantly dispersed from its planned trajectory.

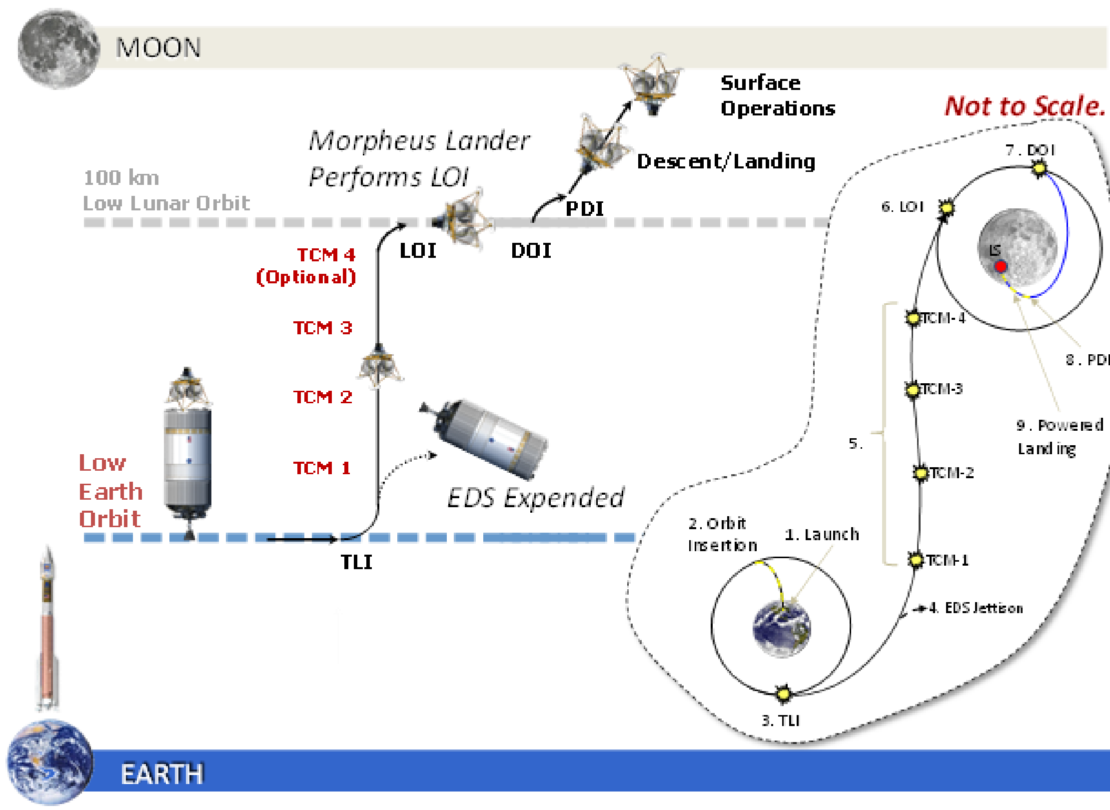

Figure 1. MARE mission overview: Bat chart (left) and Earth-moon rotating frame (right).

At lunar arrival, the LOI maneuver places the MARE spacecraft into a retrograde 100x100 km low lunar orbit (LLO). The retrograde orbit provides that the subsequent landing phase will occur in sunlight with the sun generally behind the spacecraft at a low elevation, supporting terrain relative navigation sensors and a subsequent landing near the

lunar dawn. Additionally, the selected LLO supports a minimum plane change requirement for the landing (see Figure 2). The spacecraft remains in LLO for approximately 3-4 revolutions (revs) during which time orbit determination (navigation) is conducted in support of the subsequent de-orbit and powered landing.

The descent orbit initiation (DOI) maneuver reduces the periapsis from 100 km to about 15 km altitude. Variation in the post DOI periapsis altitude does not have a strong impact on the powered descent ΔV cost, so a positive periapsis provides a once around capability in the event of a failed powered descent initiation (PDI) maneuver, thus enhancing the possibility of mission success with negligible performance impact.

Powered descent initiation (PDI) marks the beginning of the powered descent arc: a continuous main engine burn which ends with touchdown on the surface of the Moon. PDI occurs near periapsis, about a half a rev after the DOI maneuver (about an hour). The powered descent arc, targeted to the Aristarchus plateau (latitude = 23.4°, longitude = -60°, altitude = 0 m), consists of the following segments: Braking, Pitch Up/Throttle Down, Approach, Pitch to Vertical, and Vertical Descent to Touchdown. Touchdown on the surface begins the surface operations phase. PDI initiates the Braking Phase, a propellant-optimal maneuver, which uses a high throttle setting to efficiently reduce energy. Then, the Approach Phase pitches the vehicle up to 80° at reduced throttle and sets up a Hazard Detection LiDAR scan at 160 m slant range and 55° elevation from the landing site. This is followed by a 50 m Vertical Descent Phase that ends with a touchdown at the lunar surface, with a 1 m/s downward velocity. The landing is targeted such that touchdown occurs shortly after lunar dawn (with a Sun elevation of 10°), thus maximizing the amount of sunlight time for surface operations, given landing trajectory constraints.

MISSION DESIGN ASSUMPTIONS

The mission and trajectory design assumptions reflect spacecraft capability and operations requirements. They are subdivided here into the following segments: Mission Assumptions, Launch and Lunar Transfer Assumptions, Lunar Arrival Assumptions, and Lunar Descent Assumptions. The assumptions allow our mission design team to produce, to the greatest extent possible, a realistic reference mission design and associated performance trades analyses.

The nominal design and performance trades provide a framework for spacecraft subsystem design and refinement and allow the MARE team to create a spacecraft design that is ideally suited to its mission. For example, the lunar landing epoch is based upon a compromise of mission opportunity associated with Earth-Moon geometry, minimizing sun elevation angle at landing (to maximize time in sunlight for immediate post-landing surface operations), and sun elevation angle limits imposed by terrain relative navigation (TRN) and possibly other landing sensor suites.

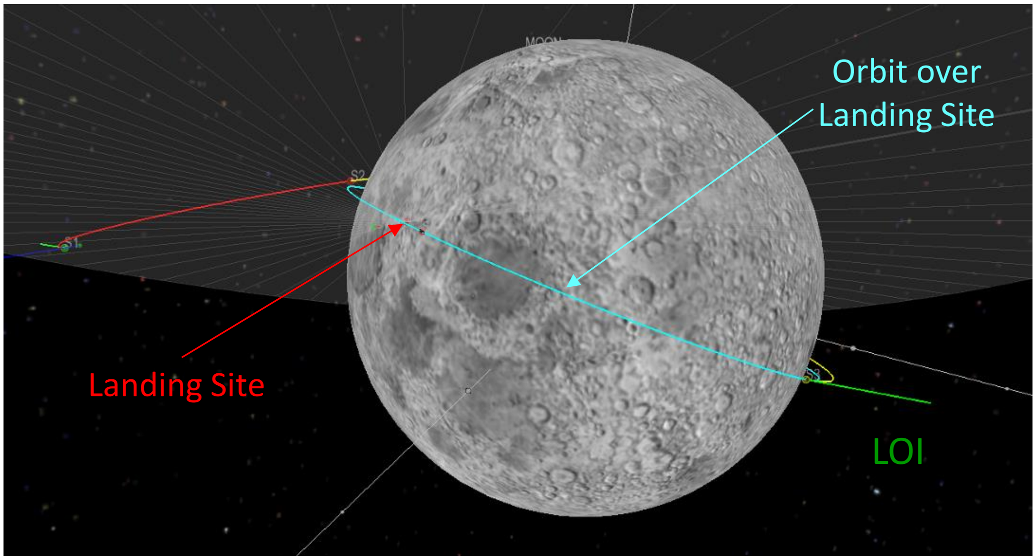

Figure 2 – Lunar transfer (red) to LOI maneuver into LLO that sets spacecraft up for coplanar landing.

DELTA-V (ΔV) SIZING BUDGET

The spacecraft has the following delta-V (ΔV) budget (Table 1). Currently, there are 3 planned trajectory correction maneuvers (TCMs) (with an option for a 4^{th}) with an overall ΔV budget of 7 m/s. The Lunar Reconnaissance Orbiter (LRO) TCM budget of 30 m/s is significantly larger. The TCM budget for this mission could be increased to 30 m/s as needed, using ΔV from the LOI budget, which is currently 100 m/s in excess of its planned nominal ΔV budget. Ongoing analysis will confirm the TCM and LOI ΔV budget and will also assess the ΔV cost of delayed TLI and DOI.

Table 1. Delta-V (ΔV) Sizing Budget.

Maneuver	Vehicle ΔV
TCM1	5 m/s
TCM2	1 m/s
TCM3	1 m/s
LOI	1000 m/s
DOI	20 m/s
PDI to Pitchover/Throttle-Down	700 m/s
Pitchover/Throttle-Down	700 m/s
Vertical Landing	600 m/s
LOI Dispersion	20 m/s
Landing Dispersion	20 m/s
RCS Control	10 m/s

PERFORMANCE TRADES

A number of ΔV performance trades were conducted to determine the spacecraft's ability to complete its part of the lunar transfer, insertion, deorbit, and landing burns. Once in a 100x100 km altitude lunar parking orbit (i.e., post-LOI), the deorbit and powered descent to landing ΔV does not change significantly. For example the difference in powered descent ΔV between a polar (90° inclination) and a retrograde near equatorial (e.g., 180° inclination) landing (due to effects of slow lunar rotation) is only about 5 m/s (with the near equatorial landing having the higher cost) out of approximately 2000 m/s for the entire deorbit and descent to landing performance requirement. The greater variation in ΔV for the Orion spacecraft occurs with the LOI burn, which is dependent upon a number of orbit trajectory parameters such as launch epoch, Earth-Moon flight time, retrograde vs posigrade lunar parking orbit (inclination), lunar landing site, etc. and operational requirements such as sun elevation angle at lunar landing and mask angle at the lunar landing site. Additionally, these parameters can also affect the TLI ΔV requirement, which can determine if the mass of the Orion spacecraft and associated payload adapters can be inserted by the Space Launch System (SLS) exploration upper stage (EUS) onto the desired TLI departure target vector. Thus, the performance analysis focuses primarily on the TLI and LOI ΔV variations.

Since the mission target date lay in the year 2021, the mission design team conducted a trade study of TLI and LOI ΔV costs across the entire year. Adherence to operational constraints such as specific lunar lighting conditions at landing (to maximize the sunlit operations duration) resulted in a set of, essentially, monthly sets of launch opportunities. Both ascending and descending node Earth departure (TLI) opportunities were examined in an effort to produce the greatest variation, hence the lowest possible TLI C3 target and/or minimum LOI ΔV.

Figure 3 shows multiple TLI opportunities and associated LOI costs for monthly sets of opportunities. For all cases examined (both ascending and descending node TLI), the TLI C3 ranges from approximately -2.12 to -1.80 km^2/s^2 and peaks near the end of 2021, in December. At this time the LOI ΔV cost is lowest with a maximum around 833 m/s. The most demanding LOI ΔV requirement occurs in the May through July 2021 timeframe. Coincidentally, the TLI C3 requirement is lowest in this same region. So the TLI C3 and the LOI ΔV requirements generally run opposite to each other … when the TLI is cheaper, the LOI is more expensive, and vice-versa.

In order to maintain flexibility in mission opportunities, the landing epoch design point reflects the most demanding LOI ΔV. Assuming the launch vehicle can provide the TLI C3 requirement, then the current LOI ΔV budget allows for 5 consecutive daily launch opportunities at every monthly opportunity throughout 2021 (see Figure 4). The daily opportunities show a range of LOI ΔVs from 835 to 885 m/s. Note that the landing epoch for this case remains fixed at the end of July 22, 2021. This reflects the need to

provide a selected (in this case, 10°) sun elevation at lunar landing, just after the lunar dawn.

These performance trades show that the current spacecraft ΔV budget possesses good flexibility to execute missions anytime throughout the 2021 year. Threats to this flexibility include drops in the ΔV budget or increases in spacecraft mass. Another impact to the ΔV budget would be including the capability of the spacecraft to accommodate a delay in TLI and/or a delay in deorbit/powered landing.

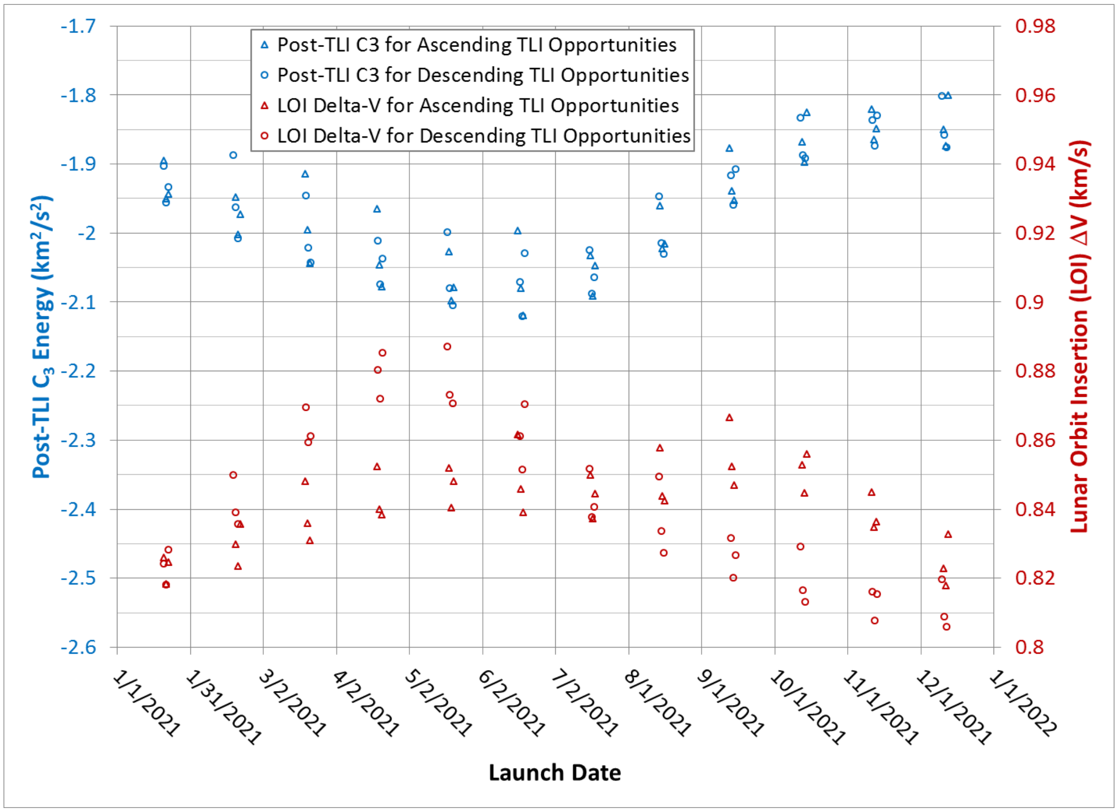

Figure 3 – TLI and LOI Performance Scan for 2021 – 3 Ascending and 3 Descending TLI Opportunities per Landing Opportunity at 10° Sun Elevation for 23.4° N, 60.0° W.

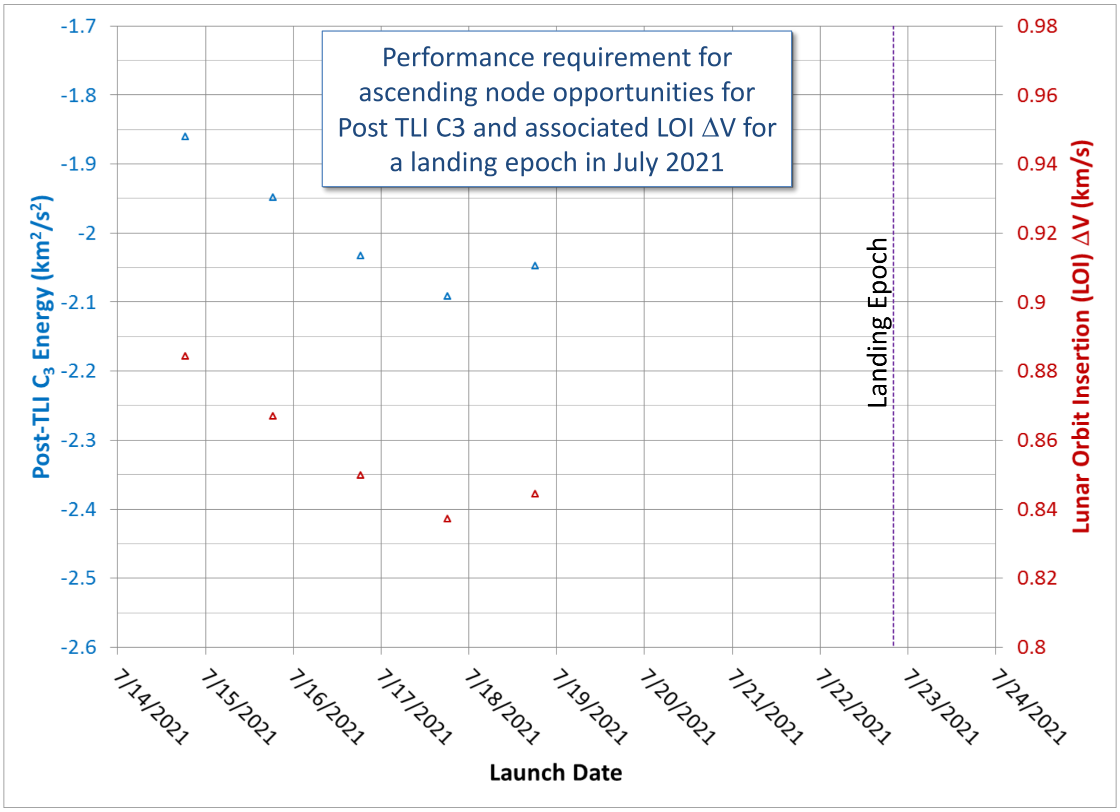

Figure 4 - TLI and LOI Performance for Launch Opportunities in July 2021 (Landing at 10° Sun Elevation for 23.4° N, 60.0° W)

LANDING OPPORTUNITIES

The launch and landing opportunities are driven by a number of sometimes interdependent parameters including, but not limited to vehicle capability (e.g., ΔV budget), operational constraints or requirements (e.g., landing at or near the lunar dawn to maximize sunlit operations time, retrograde landing approach to accommodate visual based sensors [TRN], accommodating multiple TLI revs in Earth orbit and multiple deorbit to PDI revs in lunar orbit), and planetary geometry (e.g., lunar inclination and distance at lunar arrival). These parameters affect the ΔV requirement on the spacecraft and determine if and when a launch/landing opportunity is available.

In this mission design, the spacecraft is launched first to a temporary Earth orbit in order to propagate to a phase location that provides the minimum possible TLI C3 requirement. This recommended approach is contrasted with a direct launch to TLI sequence, which is not recommended as any potential slight reduction in TLI C3 or LOI ΔV requirement would be accompanied by a restrictive performance-based launch time. Favorable geometry for the direct to TLI launch is much more infrequent than that of a launch to TLI via an intermediate Earth phasing orbit. The added requirement for a spec-

ified landing epoch (to accommodate landing lighting conditions) only serves to make direct to TLI opportunities more infrequent. The phasing Earth orbit right ascension of the ascending node (RAAN) can also be selected to minimize the TLI C3 and/or LOI ΔV, by proper selection of the launch time.

A scan of possible landing epochs was conducted using a range of sun elevation angles (at landing) and landing mask angles. For a number of reasons, the Apollo program targeted a sun elevation angle during the landing of the lunar module (LM) to be between 7° and 20°. This, combined with a retrograde orbit approach insured that the sun would be behind the LM during approach and landing, thus minimizing or eliminating sun glare on the crew. For the MARE mission, a similar approach is used, though for slightly different reasons. A 10° sun elevation angle was selected to provide sufficiently short surface feature shadows so that the TRN system would properly recognize that feature, while keeping the elevation angle low enough to move the landing as close to the lunar dawn as possible, thus maximizing the duration of daylight operations.

The region around the candidate landing sites is considered to be relatively flat, so a 5° mask angle was included in the landing opportunity calculations. This is considered to be a relatively conservative estimate and will result in a reduction in the duration of daylight operations. Note that a 10° sun elevation angle already exceeds the 5° mask angle (by 5°), so the mask angle will not restrict the lighted operations time until the end of the first lunar day.

The data shown in Table 2 represent the available lunar landing epochs, during the year 2021, which adhere to constraints of a 10° sun elevation angle and a 5° mask angle. These epochs occur approximately a month apart (due primarily to the 10° sun elevation angle requirement at landing).

For the 12 available landing opportunities (cycles) in 2021, the sun azimuth relative to the landing site ranges from 92.67° to 96.07° (slightly south of east). The actual relative azimuth angle during landing will be determined by the approach azimuth for a given mission. For example, a LLO inclination of 23.4° would result in a spacecraft final approach azimuth coming out of the east. So, in this case, the sun would be within a couple degrees of behind directly behind the spacecraft. A polar orbit landing (inclination = 90°) would have the sun nearly perpendicular to the spacecraft approach trajectory. In general, however, there is little variation in the sun azimuth over all opportunities in 2021.

There is also little variation in the 1st day sunlit durations for the 12 landing epochs in 2021. They range from 13.34 to 13.52 days. The subsequent dark times range from 15.51 to 15.78 days. A robust power and thermal design should accommodate any of these landing epochs.

Table 2. Lunar Landing - sun elevation and azimuth, mask angle, and sunlit and dark durations as a function of landing epoch for a lunar landing site at 23.4° N, 60.0° W

Cycle	Landing epoch	Sun Azimuth	Loss of Power/Sundown Epoch	Sunlit/Dark Duration	
	Sun Elevation Angle (deg)		Mask Angle (Deg)	Mask Angle (Deg)	
	10		5	5	
	(deg) ... and rising	(deg)	(deg) ... and dropping	(Days - Sunlit)	(Days - Dark)
1	January 26, 2021 20:18:44	95.67	February 09, 2021 05:18:41	13.37	15.78
2	February 25, 2021 10:52:29	96.07	March 10, 2021 19:07:16	13.34	15.76
3	March 27, 2021 00:16:07	95.97	April 09, 2021 08:24:54	13.34	15.72
4	April 25, 2021 12:21:14	95.42	May 08, 2021 21:02:43	13.36	15.65
5	May 24, 2021 23:21:04	94.60	June 07, 2021 09:02:46	13.40	15.58
6	June 23, 2021 09:44:22	93.72	July 06, 2021 20:36:36	13.45	15.53
7	July 22, 2021 20:06:47	93.02	August 05, 2021 08:01:12	13.50	15.51
8	August 21, 2021 07:02:38	92.67	September 03, 2021 19:34:43	13.52	15.53
9	September 19, 2021 18:58:10	92.78	October 03, 2021 07:33:15	13.52	15.57
10	October 19, 2021 08:06:18	93.34	November 01, 2021 20:08:16	13.50	15.64
11	November 17, 2021 22:22:45	94.20	December 01, 2021 09:24:15	13.46	15.72
12	December 17, 2021 13:25:03	95.13	December 30, 2021 23:16:17	13.41	

EXAMPLE NOMINAL MISSION TIMELINE

The nominal mission provides a good common platform to compare the individual performance of the various spacecraft subsystems. Additionally, it provides a template for doing system integration. Note that the nominal mission is not intended for vehicle sizing or to provide a ΔV budget. That said, for this proposal, the example nominal mission design is based upon a landing epoch of July 22, 2021 20:06:47. There are 3 daily launch opportunities that support this landing epoch, that are within the spacecraft ΔV budget. The July 2021 epoch is one of the more stressing cases on the spacecraft, with respect to ΔV requirement.

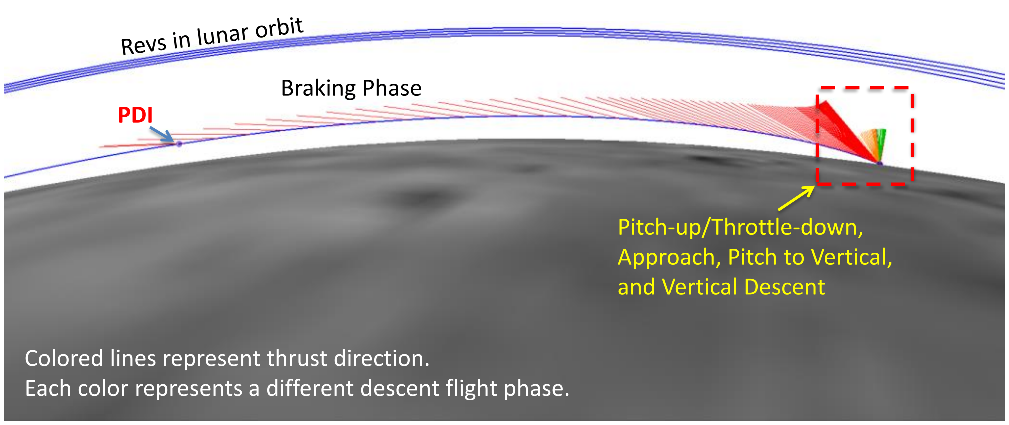

Figure 7. PDI begins the powered descent and landing sequence.

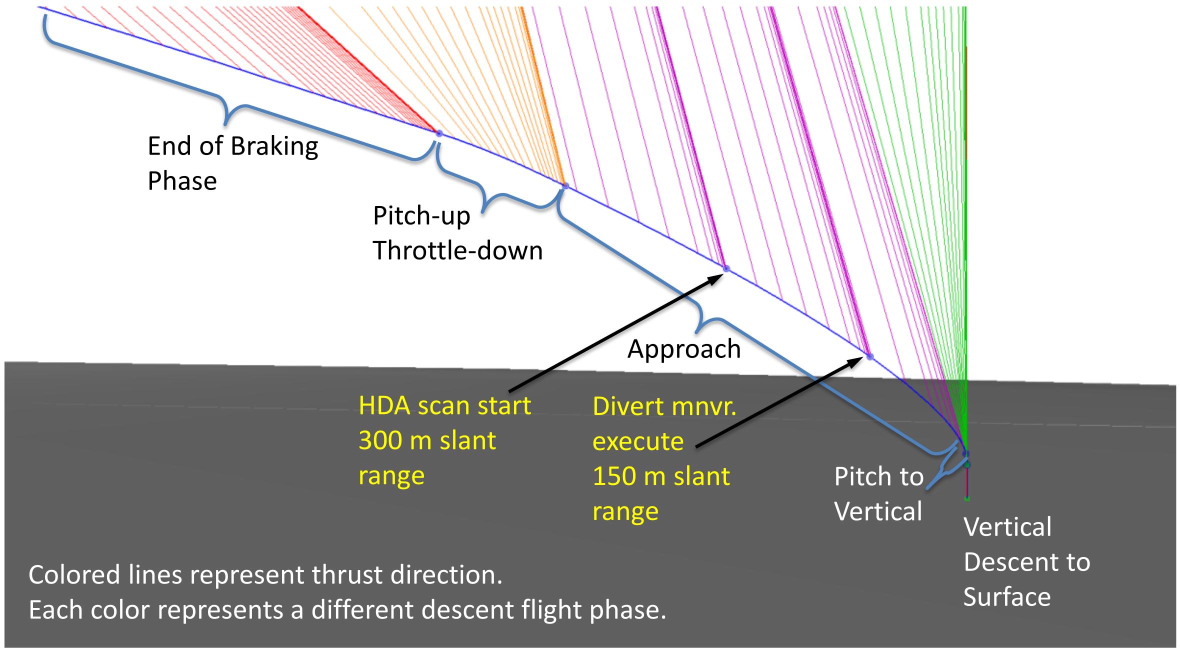

Figure 8. Powered descent landing phases.

The nominal mission at a glance is shown in Table 3. The 3 timelines represent daily mission opportunities, beginning on July 16, 2021. All missions are possible within the current proposed vehicle ΔV budget. The mission timeline covers the Epoch (expressed in Coordinated Universal Time [UTC]), mission elapsed time (MET), and Event Duration of each of the primary trajectory events. For active propulsive maneuvers, the nominal ΔV is matched with the “Active Vehicle” contributing to the maneuver. Where appropriate, comments are made about each Mission Event.

Table 3 - Nominal Mission Timeline (opening of window of daily launch opportunities). Mission Events: July 22, 2021 Landing Opportunity, 5.65 Day Transfer Duration, Landing Site 23.4° N, 60.0° W.

Mission Event	Epoch (UTC)	MET	Event Duration	Nominal ΔV	Active Vehicle	Comments
	(m/d/yyyy hh:mm:ss)	(h:mm:ss)	(h:mm:ss.s)	(m/s)		
Launch	7/16/2021 18:15:07	0:00:00	0:09:00.0	TBD: Provided by Atlas V & Centaur	Atlas V	Due East launch.
Orbit Insertion / Stage 2 MECO	7/16/2021 18:24:07	0:09:00			Centaur Upperstage	Insertion into 200 km circular LEO at 28.5 deg inclination.
LEO Coast			1:17:54.6		Centaur Upperstage	LEO Duration between 10-120 min.
TLI (Impulsive)	7/16/2021 19:42:02	1:26:55	TBD	TBD: Centaur	Centaur Upperstage	
Begin Trans-Lunar Coast			135:36:03.9		Centaur Upperstage	Transfer times from 3 to 8 days.
Jettison TLI Stage	TBD	TBD		TBD	Centaur & MARE Lander	Target Centaur US to impact moon.
TCM 1	TBD	TBD		TBD	MARE Lander	
TCM 2	TBD	TBD		TBD	MARE Lander	
TCM 3	TBD	TBD		TBD	MARE Lander	
LOI Start	7/22/2021 11:18:05	137:02:58	0:05:28.2	849.9	MARE Lander	Insertion into 100 km circ retrograde LLO.
LOI End	7/22/2021 11:23:34	137:08:27			MARE Lander	
LLO Coast			7:30:44.6		MARE Lander	3-4 revs in LLO for Nav.
DOI Start	7/22/2021 18:54:18	144:39:11	0:00:05.4	16.0	MARE Lander	DOI reduces periapse to 15 km.
DOI End	7/22/2021 18:54:24	144:39:17			MARE Lander	Assumes MARE main engine.
Descent Orbit			1:01:20.0		MARE Lander	About half a rev.
PDI / Braking Start	7/22/2021 19:55:44	145:40:37	0:09:47.4	1811.9	MARE Lander	80% throttle setting.
Pitch Up and Throttle Down	7/22/2021 20:05:31	145:50:24	0:00:44.6	72.0	MARE Lander	Reduced throttle.
Approach Start	7/22/2021 20:05:39	145:50:32			MARE Lander	Approach pitch 80°. HD Lidar scan.
Pitch to Vertical	7/22/2021 20:06:14	145:51:07			MARE Lander	
Vertical Descent	7/22/2021 20:06:16	145:51:09			MARE Lander	Vertical descent from 50 m alt.
10 m Altitude	7/22/2021 20:06:34	145:51:27	0:00:18.2	31.9	MARE Lander	Brake to 1 m/s at 10 m altitude.
Touchdown	7/22/2021 20:06:47	145:51:40	0:00:13.1	21.8	MARE Lander	Touchdown at 1 m/s

SUMMARY AND CONCLUSIONS

The JSC mission design team has a long history of developing and executing space missions (e.g., from Apollo to Shuttle to Orion, etc.). The authors have created a viable mission design profile for the MARE mission. The trajectory design has a performance budget well founded on both analysis and historical data. This report provides a working concept for structuring a launch campaign for individual (monthly) landing opportunities. It appears that the current delta-V (ΔV) budget provides more than adequate performance and may be reduced to provide mass relief to the overall spacecraft (or additional payload to the lunar surface). Preliminary results will be confirmed with ongoing, detailed trade studies.

REFERENCES

- John M. Carson III, et. al., "GN&C Subsystem Concept for Safe Precision Landing of the Proposed Lunar MARE Robotic Science Mission", AIAA Guicance, Navigation, and Control Conference, San Diego, CA, 4-8 January 2016.